Safety Benefit Analysis of Conformance Monitoring for Situation Awareness in UTM

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This work presents a novel analytical approach to address situations in drone operations when strategic coordination alone cannot ensure safety, requiring support from the Conformance Monitoring for Situation Awareness service and potentially other deconfliction services. This study focuses on evaluating the impact of off-nominal operations on both UA-to-UA collision risk and ground injury risk. It first establishes a relationship between the likelihood of off-nominal flights and the effectiveness of strategic coordination. The analysis then derives operational conditions where strategic coordination alone is insufficient to meet target safety requirements, particularly when the likelihood of off-nominal operations exceeds a certain threshold. The results indicate that higher operational tempo or density requires a lower likelihood of off-nominal operations for strategic coordination to remain effective and meet safety targets. These findings provide quantitative operational thresholds for when CMSA services are necessary. This work contributes to the safety case for both strategic coordination and CMSA services, offering analysis on when CMSA should be employed to support strategic coordination in achieving the desired safety levels. It also establishes a framework for incorporating other deconfliction services in future safety case analyses.

I. Introduction

The operations of Unmanned Aircraft Systems (UASs) in the United States continue to expand and diversify as technological advancement drives the growth of new applications across various sectors. To address regulatory and safety concerns, and to support the responsible integration of UASs into society, regulations such as Part 107 [1] and Part 135 [2] have been published. However, the challenge of promoting routine and scalable UAS operations beyond visual line of sight (BVLOS) while ensuring operational safety persists for regulators and the aviation community.

NASA, industry, and the FAA have initiated the development of a federated and automated UAS traffic management (UTM) system [3–6] to mitigate operational risk by allowing operators to share intent and coordinate operations through a system that consists of UTM Service Suppliers (USSs), a Discovery Synchronization Service (DSS), Supplemental Data Service Providers (SDSP), and an interface to the National Airspace System (NAS). This federated UTM system has undergone testing and refinement through numerous field trials, including NASA's TCL series [7–10], FAA's UTM Pilot Program (UPP) [11], Integration Pilot Program (IPP) [12], UTM Field Test (UFT) [13], and BEYOND

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Program [14]. While the UTM system shows significant promise in enabling scalable UAS BVLOS operations, the next critical challenge is to develop safety cases that demonstrate how the target level of safety can be assured by leveraging services within the UTM system. These safety cases are essential for supporting regulatory decision-making and policy development.

In the standard F3548-21 [15] published by ASTM International, the UTM community has begun developing safety cases to demonstrate how services within the strategic coordination role of the USS can significantly mitigate UA-to-UA collision risk by as much as two to three orders of magnitude, with the likelihood of off-nominal events and the level of participation being the key variables. According to F3548-21, the strategic coordination role is supported by the Strategic Conflict Detection (SCD) service and the Aggregated Conformance Monitoring (ACM) service. However, despite the initial analysis provided in the standard, two important questions remain unanswered: 1) Can strategic coordination (SCD and ACM) alone achieve the target level of safety? 2) When is the Conformance Monitoring for Situation Awareness (CMSA) service needed to support the safety case?

This work presents an analysis to determine when the strategic coordination role alone is insufficient to ensure safety, necessitating support from the CMSA service and potentially other related services. The analysis focuses on the impact of off-nominal operations on both UA-to-UA collision risk and ground injury risk. First, it establishes a relationship between the likelihood of a UAS flight going off-nominal and the effectiveness of strategic coordination. Next, it identifies operational zones where strategic coordination alone cannot meet the target safety requirements for both UA-to-UA collision risk and ground injury risk, particularly when the likelihood of off-nominal operations exceeds a certain threshold. These findings aim to assist the community in developing safety cases to demonstrate compliance with safety standards to regulators.

This paper is organized as follows: Section II provides background information on UTM services. Section III outlines the analytical approach, including the assumption used in service modeling, the workflow and the relationship between the probability of off-nominal flights and UA-to-UA collision risk. Section IV presents analysis results, focusing on two key risks: UA-to-UA collision risk and ground injury risk. Section V offers conclusions and summarizes the findings.

II. Background on UTM Services

As an initial effort to facilitate UTM-related regulations, the ASTM Committee published a standard specification for UAS Traffic Management (UTM) UAS Service Supplier (USS) Interoperability [15]. As a result of collective efforts by the community, this standard has been widely considered as a foundation for further test, implementation, analysis, and regulation development. This specification is focused on strategic aspects of UAS operations. It addresses the performance and interoperability requirements, including associated application programming interfaces (APIs), for a set of UTM roles performed by the UAS Service Suppliers (USSs) supporting UAS operations. The roles defined in this specification are: Strategic Coordination (SC), comprising the Strategic Conflict Detection (SCD) and Aggregate Operational Intent Conformance Monitoring (ACM) services; Conformance Monitoring for Situational Awareness (CMSA); Constraint Management (CSTM), comprising the Constraint Management service; and Constraint Processing (CSTP), comprising the Constraint Processing service. Table 1 presents an overview of requirements and associated roles defined in the ASTM standards.

In strategic coordination, a UA flight is mandated by the Operational Intent Creation and Modification (OPIN) to share its operational intent through "*a set of one or more contiguous or overlapping 4D volumes*" to which the flight is intended to conform with a minimum conformance level "*OiMinConformance*", typically set to 95% according to F3548-21 [15].

The Strategic Conflict Detection (SCD) service is designed "*to detect conflicts between operational intents and prevent disallowed conflicts from occurring.*" Conflicts arise when at least one constituent 3D volume of an operational intent share at least one point with a 3D volume of another operational intent, and there is an overlap between the start and end time range for those two volumes.

Meanwhile, the CMSA service provides situational awareness "*when a UA is not in conformance with its operational intent or is contingent.*" The CMSA service updates the operational intent by adding (and modifying when necessary) off-nominal 4D volumes to reflect the anticipated area of nonconformance or contingency. This updated information, off-nominal 4D operational intent volumes, allows the relevant party or system to understand the circumstances and could assist a relevant USS in taking actions to avoid conflicts with the off-nominal operational intent volumes. With the updated volumes, either strategic or tactical deconfliction can be applied to mitigate conflict.

Requirements	Role				Number of Requirements
	SC	CMSA	CSTM	CSTP	
Common Requirements	✓	✓	✓	✓	11
Operational Intent Creation and Modification	✓	✓			9
Strategic Conflict Detection Service	✓				24
ACM	✓				3
CMSA		✓			25
Constraint Management Service			✓		22
Constraint Processing Service		✓		✓	10
Logging	✓	✓	✓	✓	11
Discovery and Synchronization Service					10

Table 1 Requirements defined in ASTM F3548-21 [15]

III. Analytical Method

This section commences with the assumptions employed in modeling strategic coordination or strategic deconfliction (referred to as SD for simplification) and the CMSA service. Subsequently, the analysis approach is introduced, followed by the model detailing the impact of off-nominal flights.

A. Assumptions in Service Modeling

The strategic coordination services aim to deconflict 4D operational intent volumes (OIV) between any two flights or UAs. Previous work [16] indicates that even with operational intent volumes conforming to a 95% level, deconflicting these volumes still carries a non-zero conflict risk, influenced by various factors. By incorporating an additional buffer during volume deconfliction, the conflict risk can be reduced to a negligible level, approaching to zero. In this study, it is assumed that when the SD works effectively, the UA-to-UA collision probability or Mid-Air-Collision(MAC) risk can be reduced to zero.

Assumption 1: When the SD is applied and operational intent volumes are valid, $P(MAC|(SD \cap Valid\_OIV)) = 0$.

The CMSA service updates the operational intent volumes when a UA goes off-nominal. In real-world operations, there exists a time delay between when a UA goes off-nominal and when the updated off-nominal operational intent volume is shared in the system. For the initial analysis in this work, this time delay is neglected. However, further sensitivity analyses are recommended to assess the impact of this delay on safety and to determine appropriate time requirements for the CMSA service.

Assumption 2: When the CMSA service is active, $P(Valid\_OIV|CMSA) = 1$ with zero response delay.

Once the operational intent volumes are updated, either strategic or tactical deconfliction services need to be applied to resolve conflicts. Additionally, the deconfliction service—whether strategic or tactical—requires time, which is determined by the performance of both communication and deconfliction services. For simplicity in this analysis, the CMSA is assumed to include deconfliction services as well. This implies that once a flight goes off-nominal, the CMSA service will promptly update the operational intent volumes without any latency (Assumption 2), and the deconfliction process takes no time to ensure successful resolution of potential conflicts.

Assumption 3: When the CMSA service is on, $P(MAC|(CMSA \cap SD)) = 0$ instantaneously.

In future research, investigating the impact of deconfliction services with varying performance levels on safety should be conducted to better understand the requirements and the needs of deconfliction services.

B. Analysis Model

If off-nominal situations do not occur, the CMSA service will not provide any safety benefit. Therefore, the need for CMSA arises from an increased likelihood of off-nominal flights. When a flight goes off-nominal, its operational intent volumes become invalid or inaccurate until updated by the CMSA. Since the SD services rely on valid/accurate operational intent volumes, the presence of invalid volumes renders the SD ineffective. Hence, the first key step in this analysis is to establish the relationship between the likelihood of a flight going off-nominal and the percentage contribution of the SD, as illustrated in the upper part of Fig. 1.

This analysis assumes two extreme collision probabilities as inputs: one for situations when the SD service works effectively, and another for situations when the SD is not in use (or not effective). Once the percentage contribution of the SD is determined, the final collision probability can be calculated by weighting these two extreme situations, as shown in the lower part of Fig. 1. This model has four key inputs (as shown in blue boxes): the likelihood of a flight going off-nominal, the average number of flights per hour, the UA-to-UA collision probability with SD*, and UA-to-UA collision probability without SD. The output of this model is the overall UA-to-UA collision probability.

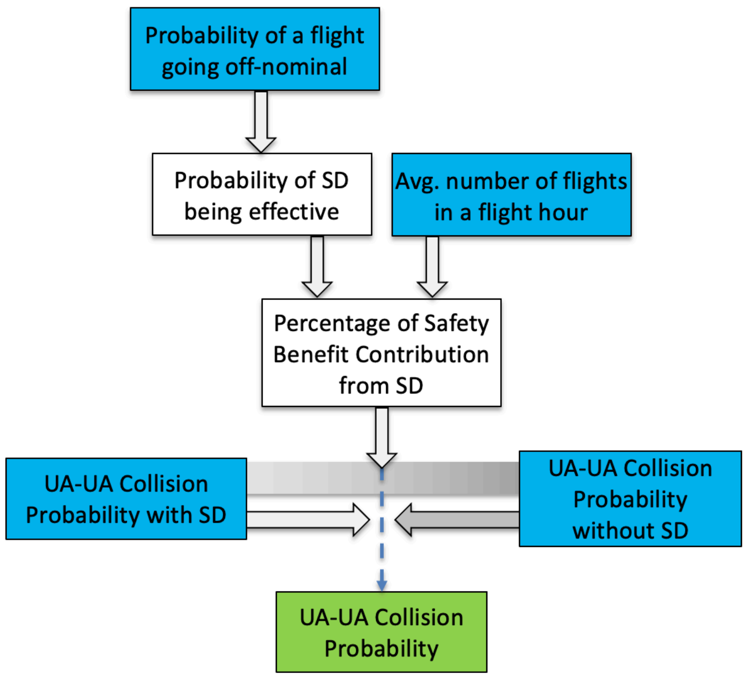


Fig. 1 Workflow in the analysis

C. Modeling the impact of off-nominal flights

Assume that the likelihood of a flight going off-nominal is uniformly distributed across its operation, and that each flight consists of an average of n operational intent volumes (OIVs), each covering the same duration of the operation. If the probability of a flight going off-nominal is $1/x$ (i.e., one out of every x flights), then the probability of a flight going off-nominal during any given OIV is:

$$P(\text{off-nominal during any OIV}) = \frac{1}{x \cdot n} \tag{1}$$

1. Relationship between the Probability of Flight Off-Nominal Situations and the Efficacy of Strategic Coordination

The ith operational intent volume (out of the total n volumes in this flight) becomes invalid if the flight goes off-nominal during any of the preceding operational intent volumes. Therefore, the probability that the ith OIV becomes invalid due to the flight going off-nominal is:

$$P(\text{OIV}_i \text{ being invalid}) = \frac{i}{x \cdot n} \tag{2}$$

*The UA-UA collision probability with SD is assumed to be zero, as stated in Assumption 1.

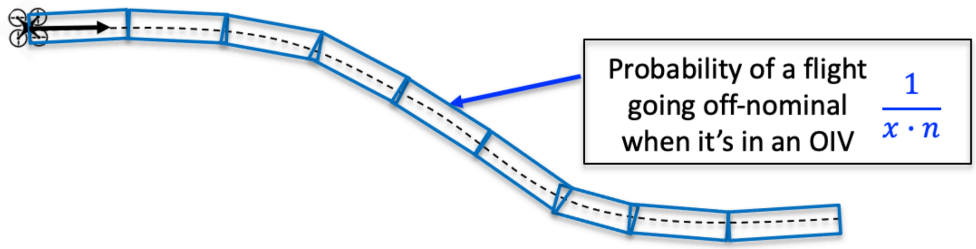


Fig. 2 Notional graph for a flight to go off-nominal while in an operational intent volume

Furthermore, the probability that any operational intent volume in a flight becomes invalid is then:

$$P(\text{invalid OIV in a flight}) = 1 - \prod_{i=1}^{n}(1 - \frac{i}{x \cdot n}) \quad (3)$$

Figure 3 compares simulation results with the analytical results from Eqn. 3 for various values of n, the number of OIVs in a flight. The simulation and analytical results are in good agreement, and as n increases, the probability approaches half of the likelihood of a flight going off-nominal:

$$P(\text{invalid OIV in a flight}) \approx \frac{1}{2x} \quad (4)$$

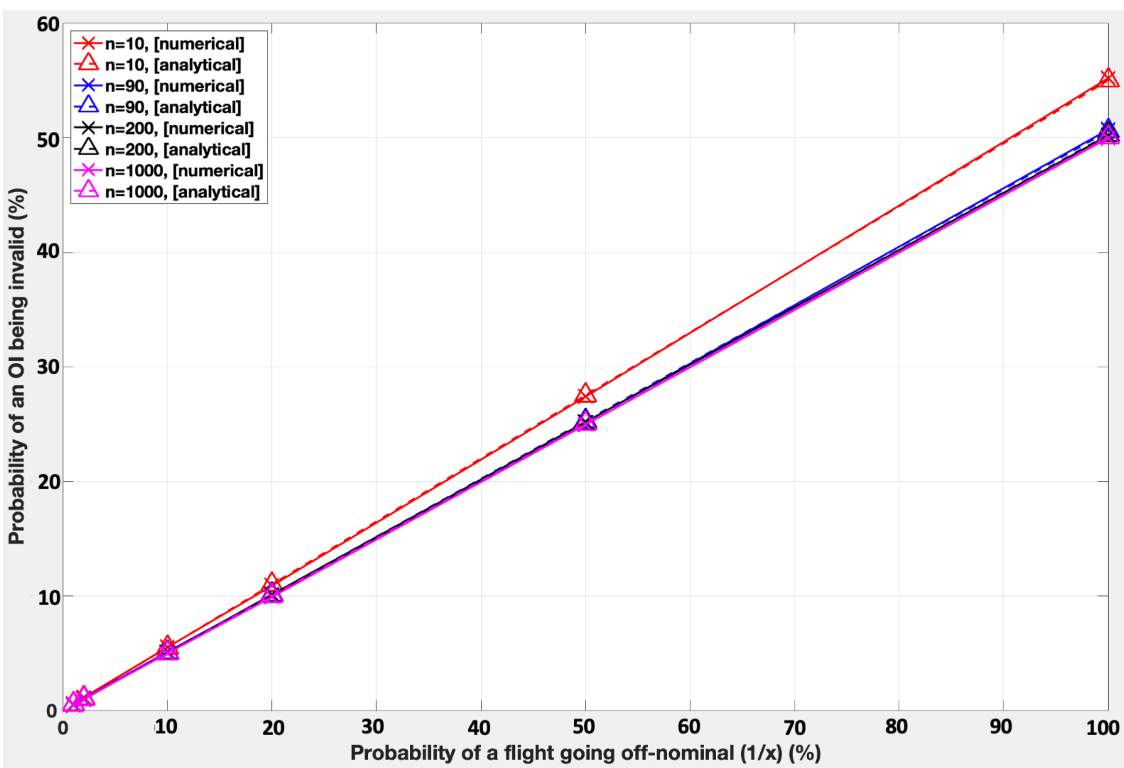


Fig. 3 Relationship between the likelihood of a flight going off-nominal and an OIV being invalid

The SD service is applied to ensure that every pair of OIVs between two flights is deconflicted. For the SD service to be effective, all OIVs in both flights must be valid. Therefore, the probability that the SD service is effective for any given pair of flights is:

$$P(\text{effective SD}|\text{a pair of flights}) = \left[\prod_{i=1}^{n}(1-\frac{i}{x\cdot n})\right]^2 \approx \left(1-\frac{1}{2x}\right)^2 \tag{5}$$

2. Safety Contribution from Strategic Coordination

Assuming that the number of flights per hour is m and that the SD safety benefit can only be realized if all OIVs are valid, the percentage of safety benefit contribution from the SD is:

$$P(\text{effective SD}|m\text{ flights}) = \left[\left(\prod_{i=1}^{n}(1-\frac{i}{x\cdot n})\right)^2\right]^{C_m^2} \approx \left(1-\frac{1}{2x}\right)^{m\cdot(m-1)} \tag{6}$$

By varying x and m, the corresponding safety benefit contribution from the SD can be plotted using Eqn. 6 (shown in Fig. 4). The figure illustrates that in scenarios with fewer number of flights per hour, a higher likelihood of off-nominal events can be tolerated to achieve the same percentage of safety contribution from the SD compared to high-density operations.

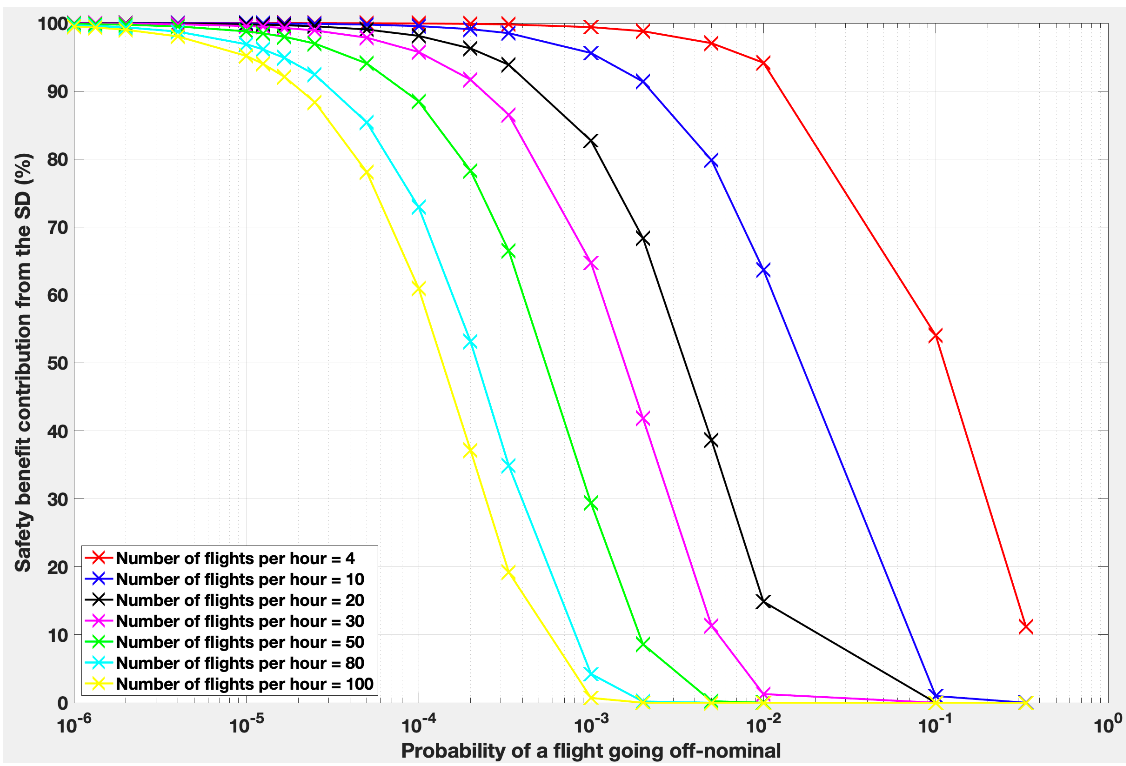


Fig. 4 Safety benefit contributed by strategic coordination

3. UA-to-UA Collision Risk

As depicted in the analysis model, once the percentage of safety benefit contribution from the SD is decided, along with the inputs for the collision probability with the SD, $P(\text{MAC}|\text{SD})$, and the collision probability without the SD, $P(\text{MAC}|\text{SD'})$, the final UA-to-UA collision probability can be calculated as follows:

$$P(\text{UA-to-UA collision risk}) = P(\text{MAC}|\text{SD})\cdot P(\text{effective SD}|m\text{ flights}) + P(\text{MAC}|\text{SD'})\cdot[1-P(\text{effective SD}|m\text{ flights})] \tag{7}$$

IV. Analysis Results

Building upon the relationships established in the previous section, this section presents analysis results driven by two different risks: UA-to-UA collision risk and ground injury risk.

A. Results driven by UA-to-UA collision risk

Using Eqn. 7 and assuming $P(\text{MAC}|\text{SD}) = 0$ when SD is effective (Assumption 1), the percentage of safety benefit contribution from the SD, $P(\text{effective SD}|m \text{ flights})$, required to achieve a target level of UA-to-UA collision risk can be derived as follows:

$$P(\text{effective SD}|m \text{ flights}) \geq 1 - \frac{\text{Target UA-to-UA collision risk}}{P(\text{MAC}|\text{SD'})} \tag{8}$$

The acceptable off-nominal probability, $1/x$, for different operational tempos (number of flights per hour, m), can then be derived from Eqn. 6 and 8:

$$\frac{1}{x} \leq 2 \cdot \left(1 - \sqrt[m\cdot(m-1)]{1 - \frac{\text{Target UA-to-UA collision risk}}{P(\text{MAC}|\text{SD'})}}\right) \tag{9}$$

1. Operational Conditions When Strategic Deconfliction is Insufficient to Meet the Target Risk Level

Assuming a collision probability without the SD is 10^{-4}, and a target UA-to-UA collision risk of 10^{-7}, the highest acceptable off-nominal probability for different levels of operational tempo (the number of flights per hour, m) can be calculated using Eqn. 9. Fig. 5 shows the resulting curve for different values of m. The red region represents the operational conditions where the SD alone cannot meet the target level of safety, with the analysis in this section focused on UA-to-UA collision risk.

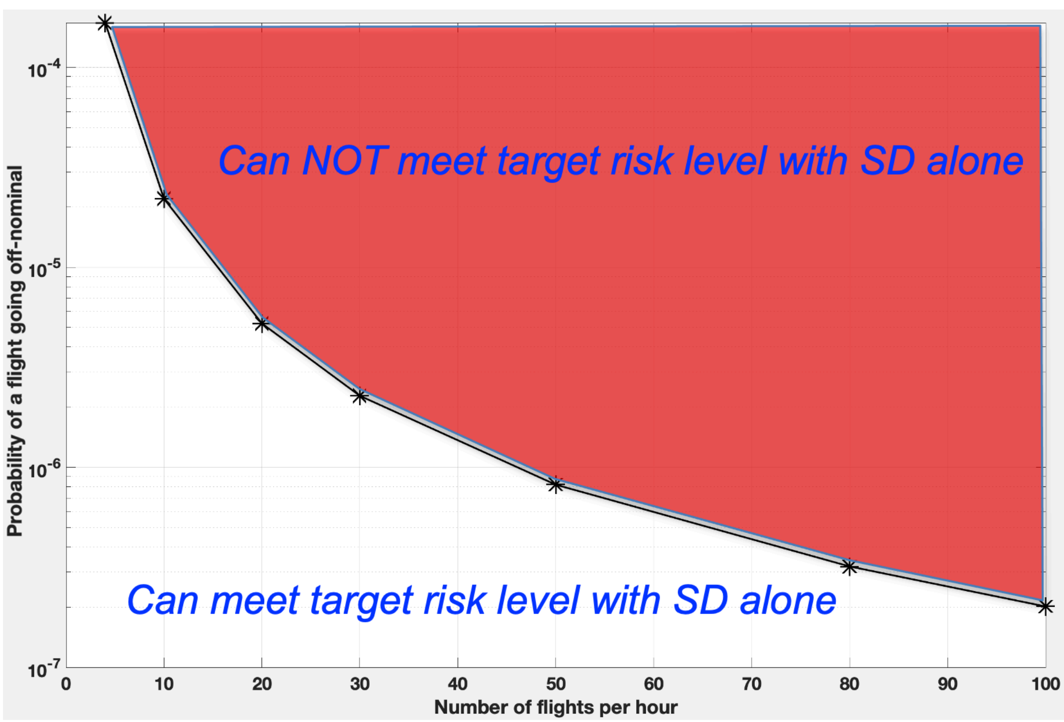


Fig. 5 Operational conditions when Strategic Deconfliction alone is inadequate

2. *Impact of Operational Complexity*

As operational complexity increases, the collision probability without the SD, $P(\text{MAC}|\text{SD'})$, also increases. Fig. 6 illustrates the boundaries for different complexity levels. In low-complexity or low-density scenarios, the collision probability without the SD, $P(\text{MAC}|\text{SD'})$, is low, allowing a higher likelihood of off-nominal situations for the SD to remain effective, compared to scenarios with higher complexity.

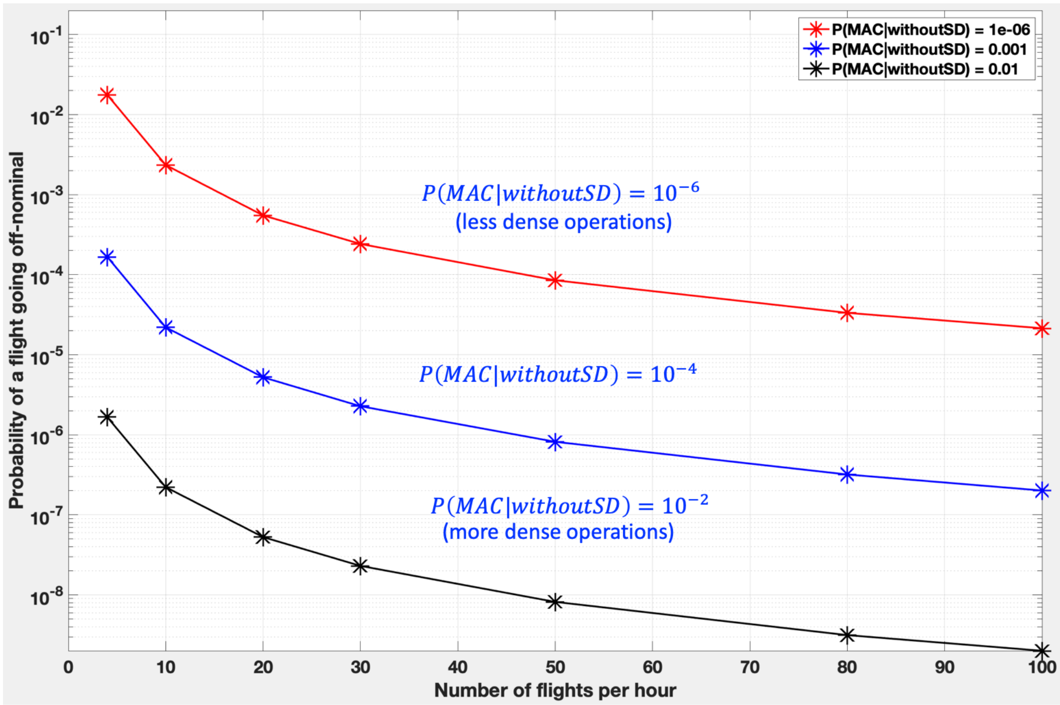


Fig. 6 Thresholds when CMSA is required to achieve the target UA-to-UA collision risk level

B. Results Driven by Ground Injury Risk

The direct cost of a UA-to-UA collision is considerably lower than that of a collision between manned aircraft, as UAs do not carry pilots or passengers, and they are typically smaller and less expensive than manned aircraft. As a result, the risk of ground injuries resulting from a UA-to-UA collision is generally considered a more critical factor than the collision risk itself.

1. *Kinetic Energy and Impact Area*

According to AC 107-2A [17], to ensure that a small UA does not exceed the applicable injury severity limit upon impact with a human being, the FAA-provided means of compliance (MOC) defines the following speed limits for UAs of different weights:

Assume the UA is traveling at a speed of 15 mps (or 29 knots) just before the collision, which occurs at an altitude of 400 ft (or 122 meters). The magnitude of the velocity of the drone as a whole after the collision † can be approximated as follows:

$$|\vec{V}| = \sqrt{{v_0}^2 + 2 \cdot g \cdot h} \geq 51.1 \text{ mps (114 mph)} \tag{10}$$

In this analysis, air resistance is neglected. Assuming the UA weighs 2 lbs, a speed of 114 mph is approximately six times greater than the 19 mph specified in Table 2 for Category 3. For any fragment heavier than 1/36 of the original drone's weight, its kinetic energy will exceed the threshold defined in AC107-2A. Therefore, the number of fragments capable of generating kinetic energy above the specified requirement will not exceed 36. Assuming each fragment impacts an area of one square meter (or about 10.8 square feet), the worst-case scenario for a collision between two

† Assume that the fragments of the drone after the collision remain close to each other and move at similar speeds

	Maximum speed (mph)	
Weight (lbs)	Category 2 (11 ft-lbs)	Category 3 (25 ft-lbs)
1.0	18	27
1.5	15	22
2.0	13	19
2.5	11	17
3.0	10	16

Table 2 Speed limits defined by the FAA-provide MOC [17]

drones would result in a total impact area of 72 m^2 (775 ft^2), with the kinetic energy surpassing the limits specified in AC107-2A.

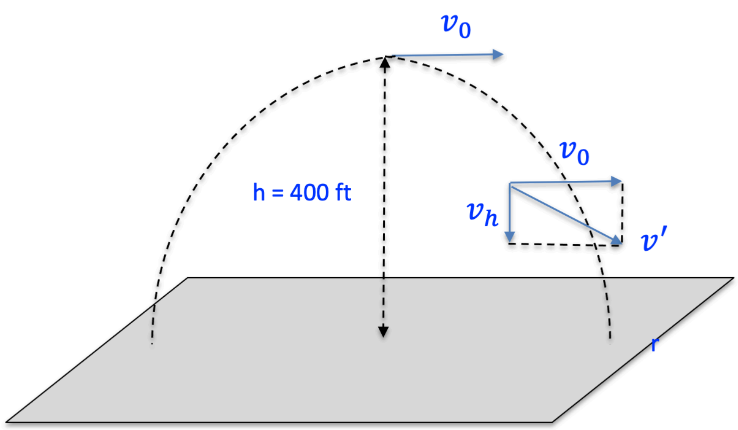
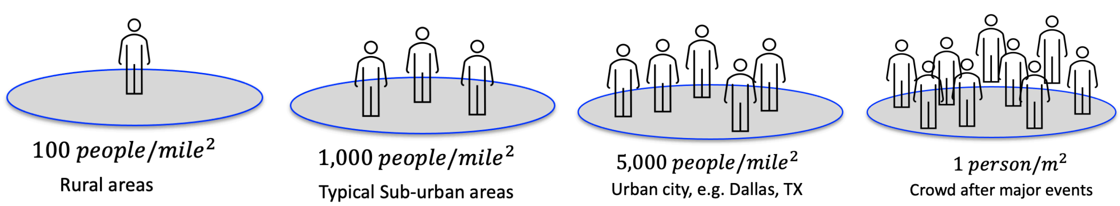


Fig. 7 Kinetic energy computation after MAC

2. Ground Injury Risk due to A UA-to-UA Collision

To assess the ground injury risk resulting from a collision, population density is considered as a key factor. To facilitate the computation, population density is categorized into four groups: rural areas (100 people per square mile), suburban areas (1,000 people per square mile), urban areas (5,000 people per square mile), and high-density areas (one person per square meter).



(a) Rural area (b) Suburban area (c) Urban area (d) Crowd after a major event

Fig. 8 Areas with varying population densities

As assumed in the previous section, a UA-to-UA collision results in serious damage over a total area of 72 m^2 (the worst-case scenario). The average number of ground injuries per collision, ($N(Injury|MAC)$), for various population densities can then be computed, as shown in the Table 3:

Area Type	Population Density	Number of injuries per MAC
Rural area	100 people/mile^2	$N(Injury\|MAC) = 0.003$
Suburban area	1,000 people/mile^2	$N(Injury\|MAC) = 0.014$
Urban area	5,000 people/mile^2	$N(Injury\|MAC) = 0.06$
High-density area	1 person/meter^2	$N(Injury\|MAC) = 72$

Table 3 Ground injury risk per MAC and area type

3. Operational conditions when Strategic Deconfliction is insufficient

Given the number of injuries, $N(Injury|MAC)$, and the UA-to-UA collision probability or risk, the total ground injury risk can then be expressed as Eqn. 11, where P(UA-to-UA collision risk) is defined in Eqn. 7.

$$P_g(\text{Ground Injury Risk}) = N(Injury|MAC) \cdot P(\text{UA-to-UA collision risk}) \tag{11}$$

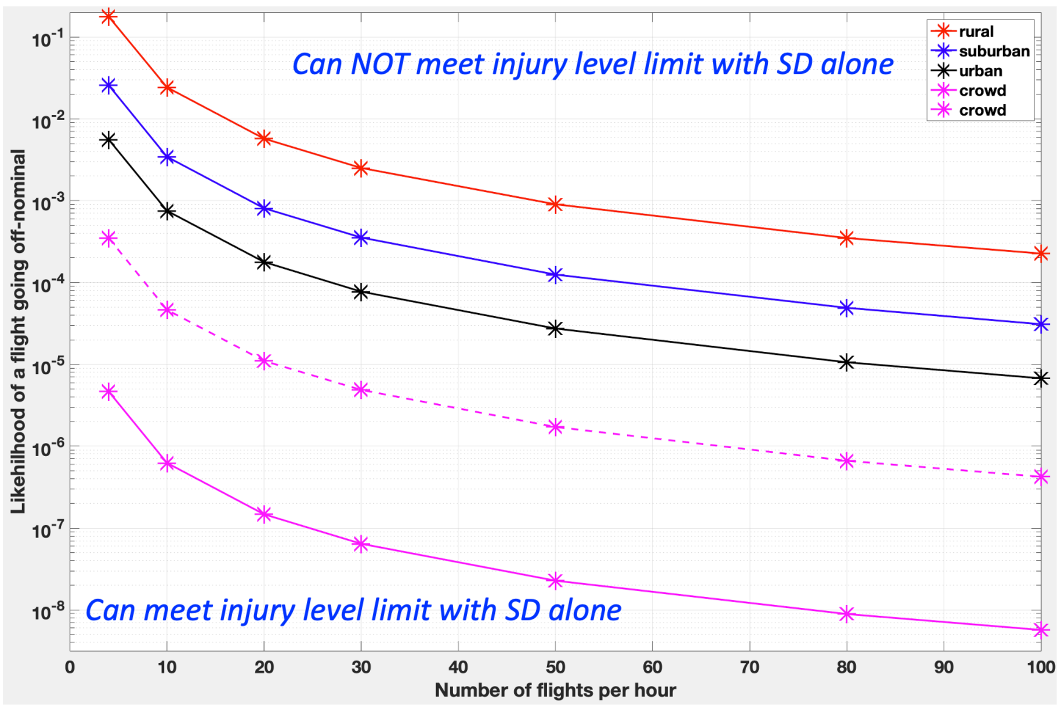


Fig. 9 Thresholds when CMSA is required to achieve the target ground injury risk risk level

Once a target ground injury risk P_g is specified, the corresponding target UA-to-UA collision risk can then be derived using Eqn. 11. This, in turn, allows for the calculation of the acceptable off-nominal probability, $1/x$, using Eqn. 9. According to the National Safety Council [18], the approximate fatality rates for scheduled airline services, nonscheduled airline services, and general aviation operations are 0.15, 1.0, and 6.0 per 100,000 flight hours, respectively. Using a target ground injury risk of 1.5×10^{-5} per flight hour[‡], and assuming the collision probability without the SD is 10^{-4}, the operational boundary where SD alone can or cannot meet the target ground injury level is shown as the dashed line in Fig. 9. It is noted that only the high-density crowd case showed up (magenta color). For the other three cases, the ground injury level remains within the target, regardless of off-nominal probability, due to the low population density. If the target injury risk is reduced to 2.0×10^{-7}[§] the corresponding operational boundaries are shown as the solid curves in Fig. 9, where the high-density area requires a significantly lower likelihood of off-nominal flights compared to rural areas.

[‡]This is equivalent to 766 injuries each year, assuming 10,000 operations per hour and 14 hours of operations each day

[§]This is equivalent to 10 injuries each year, assuming 10,000 operations per hour and 14 hours of operations each day

V. Conclusions

This work presented a novel analytical approach to address situations when strategic coordination alone cannot ensure safety, necessitating support from the CMSA service and possibly other deconfliction services. The approach focused on analyzing the impact of off-nominal operations on both UA-to-UA collision risk and ground injury risk. Initially, a relationship is established between the likelihood of a UAS flight going off-nominal and the effectiveness of strategic coordination. Operational conditions are then derived for cases when strategic coordination alone cannot meet target safety requirements if the likelihood of off-nominal operations exceeds a certain threshold. The analysis considered two primary risks: UA-to-UA collision risk and ground injury risk.

The results revealed that higher operational tempo or density requires a lower likelihood of off-nominal operations for strategic coordination to remain effective and meet the target level of safety. For instance, when 50 flights are operating per hour, CMSA is required if the likelihood of off-nominal flights exceeds 10^{-8} in order to meet the target level of safety for UA-to-UA collision. Additionally, when using ground injury risk as the target safety metric, to reach the level of ground injury risk similar to commercial aviation operations, CMSA will not be required until the likelihood of off-nominal flights exceeds 10^{-6}.

This study provides a comprehensive analysis of the thresholds at which CMSA services are needed under various operational conditions. This work contributes to the development of safety cases for both strategic coordination and CMSA services, offering quantitative evidence on when CMSA services should be employed to support strategic coordination in achieving the desired safety levels.

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